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Managing fisheries to conserve the Antarctic marine ecosystem: practical implementation of the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR)

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We aim to identify the important steps in the evolution of the ecosystem approach to management under the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR). The first section provides the background to CCAMLR, including the formulation of the convention and its objectives, its operation, and the historical trends in fisheries. Later sections describe (i) the reasons why a precautionary approach to setting catch limits evolved, (ii) how the precautionary approach takes account of ecosystem objectives and provides for the orderly development of new fisheries, and (iii) how the use of ecosystem indicators in the setting of catch limits and for monitoring the effects of fishing is being evaluated. The final section describes the general framework being used to develop a feedback-management system that incorporates objectives, target species assessments and ecosystem assessments. The CCAMLR experience provides two important lessons. First, conservation objectives can only be achieved by implementing management measures, even when very little is known. Second, methods were found for achieving scientific consensus despite the uncertainties surrounding estimates of parameters and the behaviour of the system. CCAMLR is yet to face the real test in its ecosystem approach, the development of the krill fishery. Before this occurs, appropriate management procedures have to be developed to avoid localized effects on the ecosystem and to provide effective feedbacks on the effects of fishing through its monitoring programme.

Key words: ecosystem management, icefish, krill, management strategies, precautionary approach, toothfish.

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Introduction

The Southern Ocean has experienced notable collapses of marine species following exploitation, including seals in the 19th century, the great whales in the middle of the 20th century, the marbled rockcod (*Notothenia rossii*) in the early 1970s and, most recently, some stocks of the Patagonian toothfish (*Dissostichus eleginoides*). Amidst this background of over-exploitation, regulation of harvesting activities in the Antarctic has been attempted through a series of international conventions: the 1946 International Convention for the Regulation of Whaling, administered by the International Whaling Commission (IWC), the 1972 Convention for the Conservation of Antarctic Seals (CCAS) and the 1980 Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR). The IWC and CCAS govern the exploitation of marine mammals in the

Antarctic and exploitation of these species will not be considered here. CCAMLR has a much wider mandate; it was the first international convention involving fisheries to include wide-ranging conservation principles in its objectives based on an ecosystem approach. Since its first meeting in 1982, the Commission of CCAMLR has grappled with balancing the demands of fisheries with the requirement to ensure the Southern Ocean ecosystem is not negatively affected by those fisheries. Despite the noble intentions of the convention, progress towards achieving these objectives was slow and *ad hoc* in its first 10 years. In recent years, it has gathered momentum with the advancement of methodologies that will assist in the overall development of a systematic approach to management of Antarctic fisheries and conservation of the Antarctic marine ecosystem.

We aim to identify the important steps in the evolution of CCAMLR. In particular, we describe (i) the reasons why a precautionary approach has evolved to setting catch limits, (ii) how the precautionary approach takes account of ecosystem objectives and provides for the orderly development of new fisheries, and (iii) how the use of ecosystem indicators in the setting of catch limits and for monitoring the effects of fishing is being evaluated. We then describe the future work required to further elaborate and implement ecosystem-orientated management procedures.

Background

CCAMLR and its objectives

CCAMLR is part of the Antarctic Treaty System. The development of a legal regime to manage the exploitation of Antarctic marine living resources began after the Antarctic Treaty Consultative Parties agreed in 1977 to negotiate a convention to prevent over-exploitation of Antarctic krill (*Euphausia superba*), a key prey species. Over-exploitation of krill seemed imminent given the over-exploitation of other Antarctic species, notably whales (Edwards and Heap, 1981). Also, action was considered necessary to ensure that exploitation of krill did not inhibit the recovery of whale and seal populations taken close to the brink of extinction.

In the formative years, the effect of krill fishing on krill predators was of paramount concern. This arose because of the apparent simplicity of the Antarctic marine ecosystem, which is often assumed to comprise roughly three trophic levels – primary production, krill, and krill predators (seals, whales, and seabirds). Less recognition has been given to other predators of krill, such as fish and squid, and the role that toothed whales may have in the system, even though higher predators in some parts of the Antarctic are not dependent on krill in the same way as in the South Atlantic.

Figure 1 shows the major components of the krill-based trophic system around South Georgia Island in the South Atlantic and the linkage to the three main fisheries discussed below. The removal of krill and baleen whales from this figure leaves the system as it appears at Heard Island in the Indian Ocean, reflecting a spatial shift in trophic structure between Subantarctic areas. A similar shift also occurs periodically around South Georgia at times when krill abundance is low. At these times, predation on icefish by fur seals increases substantially (Agnew *et al.*, 1998).

CCAMLR was signed in 1980 and the first meeting was in 1982. Its area of influence includes the area south of the Antarctic Polar Front (formerly known as the Antarctic Convergence; Fig. 2). Within this zone, it endeavours to enable rational use of marine species while ensuring principles of conservation are maintained. These principles aim to ensure the maintenance of stable recruitment in target species, the maintenance of the ecology of the system, particularly in relation to predators of those target species, and that the ecosystem effects of fishing must be reversible over a fixed period. These principles are contained in paragraph 3 of Article II of the Convention, such that:

3. Any harvesting and associated activities in the area to which this Convention applies shall be conducted in accordance with the provisions of this Convention and with the following principles of conservation:

(a) prevention of decrease in the size of any harvested population to levels below those which ensure its stable recruitment. For this purpose its size shall not be allowed to fall below a level close to that which ensures the greatest net annual increment;

(b) maintenance of the ecological relationships between harvested, dependent and related populations of Antarctic marine resources and the restoration of depleted populations to the levels defined in sub-paragraph (a) above; and

(c) prevention of changes or minimization of the risk of change in the marine ecosystem which are not potentially reversible over two or three decades, taking into account the state of available knowledge of the direct and indirect impact of harvesting, the effect of the introduction of alien species, the effects of associated activities on the marine ecosystem and of the effects of environmental changes, with the aim of making possible the sustained conservation of Antarctic marine living resources.

Article IX provides the means by which the Commission can manage fisheries. It includes that the Commission must base decisions on the best scientific evidence available. Decisions pertaining to controls on fisheries are embodied in conservation measures. These are binding in international law on signatories to the Convention. Non-binding but agreed principles are often embodied in resolutions. Decisions are made by consensus. Consequently, changing the attitudes of the Commission is very difficult.

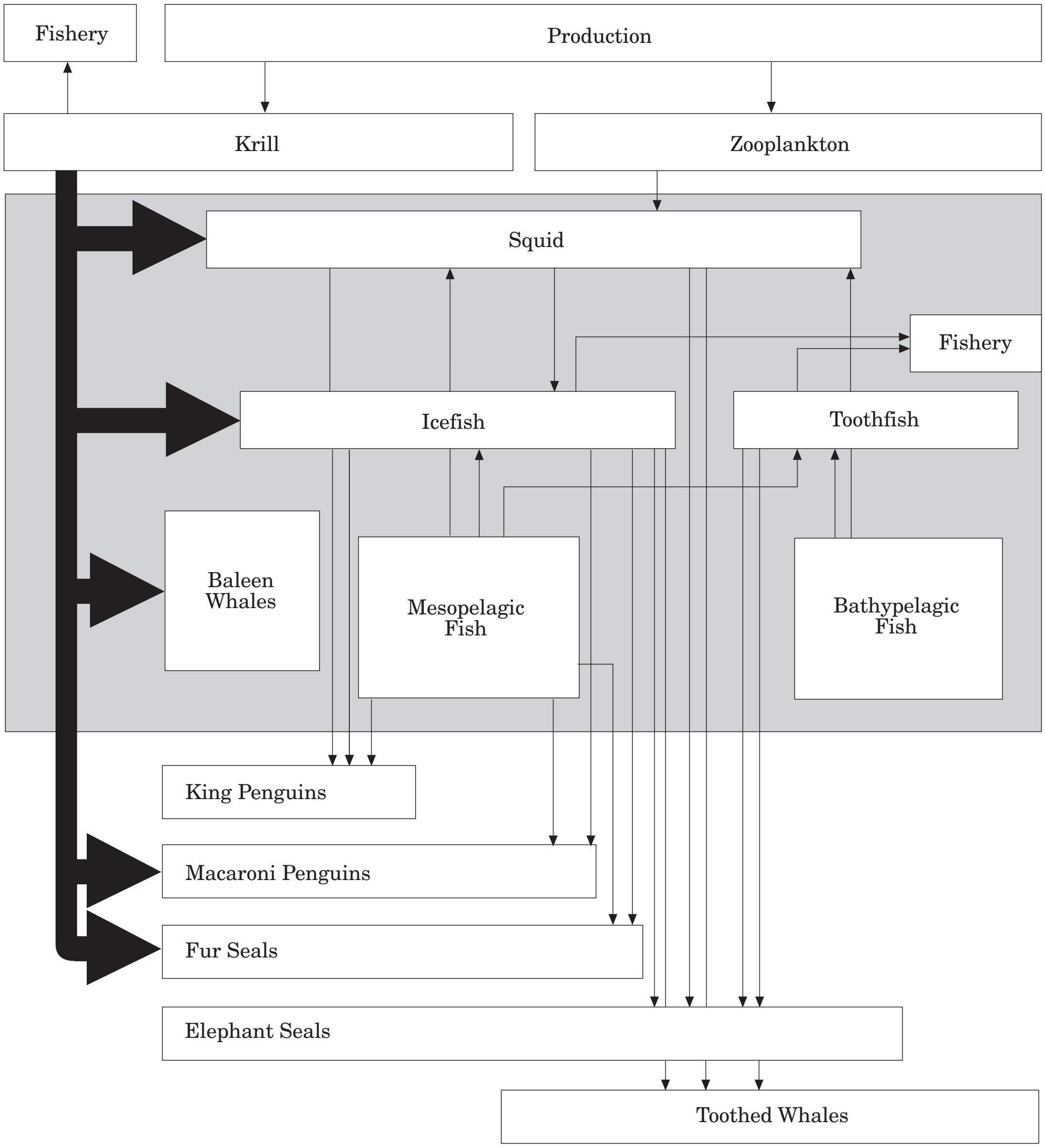

Figure 1. Structure of the food web around South Georgia Island in the Atlantic Ocean, including the fisheries for krill, Patagonian toothfish, and mackerel icefish. The grey box represents the pelagic system that depends on krill and other zooplankton.

The Commission now comprises 23 members and receives advice from a Scientific Committee. A Working Group on Developing Approaches to Conservation (1987–1990) began the task of interpreting the Convention's objectives and providing mechanisms for making ecosystem-oriented decisions rather than concentrating on individual species. Working groups of the Scientific Committee include Fish Stock Assessment (WG-FSA), Ecosystem Monitoring and Management (formerly the Working Groups on Krill and on the CCAMLR Ecosystem Monitoring Program), and Incidental Mortality Arising from Longline Fishing (currently part of WG-FSA).

History of Antarctic fisheries

Commercial exploitation of krill began in the early 1970s. By 1982, krill catches had risen to a peak of 528 201 t. Catches then declined sharply until 1983/84 as a result of marketing and processing problems induced by the discovery of high levels of fluoride in the exoskeleton of krill (for review see Nicol and Endo, 1997).

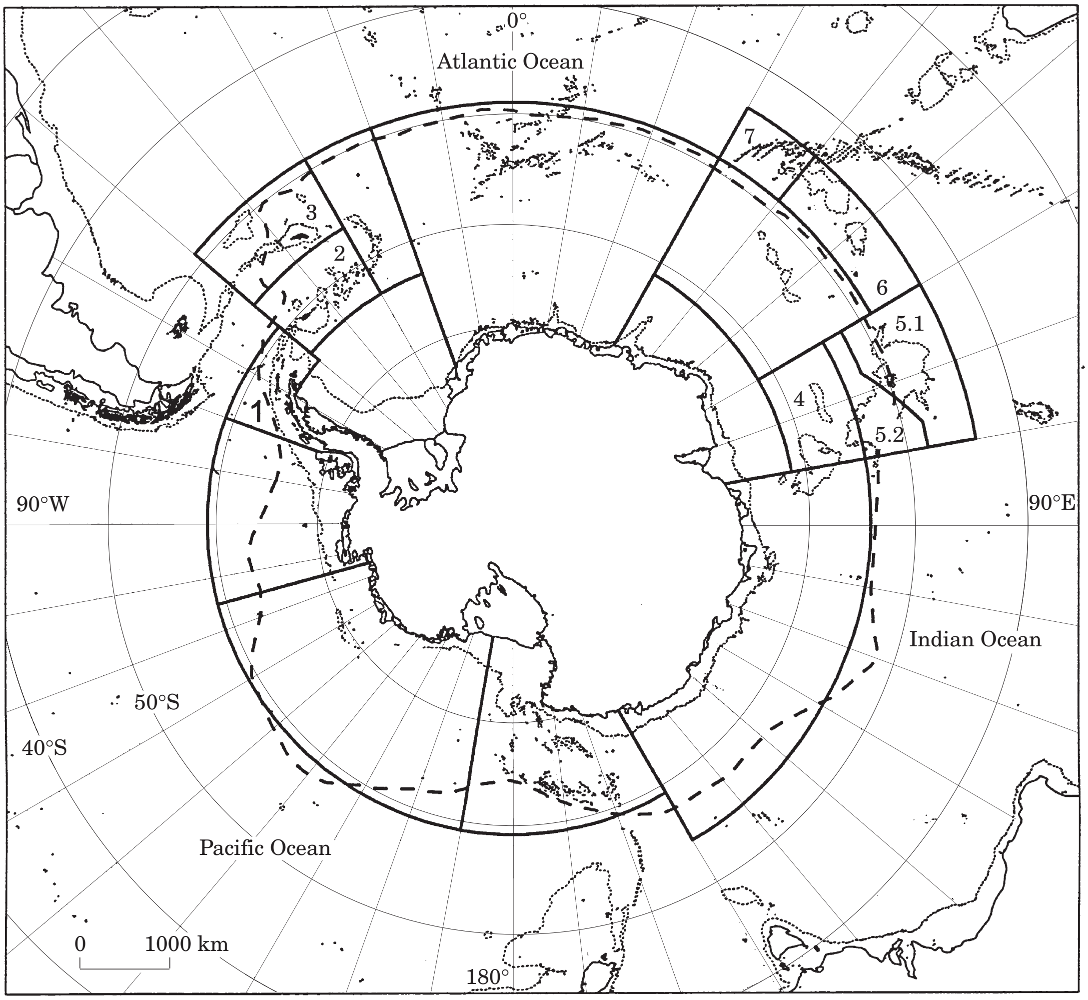

Figure 2. Map of the Southern Ocean showing the boundary to the CCAMLR area and its statistical subareas and divisions (solid bold lines), the Antarctic Polar Front (dashed line), continental boundaries (solid lines), and the 2000 m bathymetric contours in the region (dotted lines). The numbers refer to: 1. Antarctic Peninsula and integrated study area; 2. South Orkney Islands; 3. South Georgia Island and integrated study area; 4. Prydz Bay integrated study area; 5.1. Kerguelen Island; 5.2. Heard Island and McDonald Islands; 6. Crozet Island; 7. Prince Edward and Marion Islands.

These problems were overcome and catches increased again until the break-up of the Soviet Union in 1991 caused another sharp decline in catches. Most krill fishing occurs in the South Atlantic around South Georgia Island in winter and around the Antarctic Peninsula and South Orkney Islands in summer. The total catch currently is around 80–100 000 t, well under the current precautionary catch limits.

Most finfishing has occurred around South Georgia Island, constituting 58% of the total reported finfish catch of 3 million tonnes taken in the period 1969–1997 from the CCAMLR area (CCAMLR Statistical Bulletins). The next most important areas have been around Kerguelen Island in the Indian Ocean and the South Orkney Islands in the South Atlantic. Koch (1992) provides a thorough history of finfisheries in the Antarctic.

The exploitation of finfish began in the mid-1960s with the expansion into the region of fishing operations of the Soviet and other eastern-bloc nations. In two years from 1969, the bottom-dwelling marbled rockcod had almost gone from around South Georgia Island after 514 000 t were taken. Stocks around other islands followed a similar fate. By the end of 1980, this species was depleted throughout the Antarctic along with other species caught in bottom trawls, such as *Gobionotothen gibberifrons* and *Lepidonotothen squamifrons* (Agnew and Nicol, 1996; Koch, 1992). Marbled rockcod remains at less than 5% of its pre-exploitation abundance. Two species are currently exploited – the Patagonian toothfish and the mackerel icefish (*Champsocephalus gunnari*).

The Patagonian toothfish is a large (1.5–2 m), long-lived (35–50 years), deep-water species. Fishing for this species began in the 1970s as part of the mixed bottom-trawl fishery around South Georgia Island and Shag Rocks. Interest increased with the introduction of long-lining in 1987, enabling exploitation of the larger, older fish found in areas inaccessible to trawlers. Trawl fisheries tend to take juvenile fish while long-line fisheries take reproductively mature fish. Long-lining is now the principal method of exploitation, although trawling still occurs around Heard, Kerguelen, and Crozet Islands.

Catches taken by vessels not co-operating with CCAMLR obligations are illegal (when taken in the Exclusive Economic Zone of a sovereign state), unregulated (when taken by non-members), or unreported (when taken by members). Illegal, unregulated, and unreported (IUU) catches initially started around South Georgia but, in 1996, a rapid rise in activities in the Indian Ocean began, leading to a substantial catch above the recommended aggregate global limit for the Convention area. Even though IUU catches have been reduced in recent years, the threat of these activities to the sustainability of stocks is great, as exemplified by the rapid decline of the stock around Crozet Island in 1997 (SC-CAMLR, 1997).

The mackerel icefish is a shallow-water (100–350 m), short-lived (<6 years) species with separate stocks supporting fisheries around South Georgia, Kerguelen, and Heard Islands. The history of these fisheries has been similar to that of notothenid fisheries. Mackerel icefish became a target of the Soviet fleets when abundance of marbled rockcod had declined by the mid-1970s. The considerable variation in recruitment led to large fluctuations in catches around South Georgia and around Kerguelen Island, where most of these fisheries were undertaken. However, the mean annual catch declined over the first 20 years (Koch, 1992). The fisheries for mackerel icefish are the only viable fin fisheries to remain from those undertaken prior to CCAMLR.

Managing finfish catches, 1984–1994

In the early years of CCAMLR, the management of finfisheries relied on then existing standard methods for stock assessment and yield predictions. This period was an important precursor to the development of the current approaches to assessments that explicitly deal with uncertainties in knowledge and with the ecosystem perspective.

The Working Group on Fish Stock Assessment was first convened in 1984 (the third meeting of CCAMLR) as an ad hoc working group of the Scientific Committee. Until this time, the evaluation of the status of Antarctic fish stocks was undertaken by a Scientific Committee on Antarctic Research (SCAR) Working Party on Fish Biology, which concluded that Antarctic fish were susceptible to overfishing owing to their life-history characteristics, but which had insufficient data to undertake full stock assessments (Koch *et al.*, 1985; Koch, 1992).

Most attention was given to the status of marbled rockcod around South Georgia. Despite the incomplete data set and lack of detailed analyses, there was sufficient evidence to recommend a closure of 12 nautical miles around South Georgia, mesh size regulations and a reduction in catches to below the levels caught in the early 1980s. While the first two recommendations were adopted by the Scientific Committee and set into conservation measures by the Commission, the recommendation to restrict catches was opposed by only a few members in the Scientific Committee (SC-CAMLR, 1984) on the basis that the information and the analyses were incomplete. Despite a prohibition of directed fishing for marbled rockcod in the following year, this confrontation set the tone of discussions for the remainder of the 1980s and the implementation of important measures to protect depleted stocks often lagged behind the advice by one to two years. These confrontations increasingly raised the question "How should the Commission deal with uncertainty in assessments and advice from the Scientific Committee?" Uncertainties arose from natural variation in stock abundance and statistical error in stock assessment, uncertainty in estimates of model parameters, incomplete historical catch records, and imprecise submission of recent data. They also arose in the decision-making process generally because of the assessment methodologies available at the time.

The problem manifested itself when the mostly non-scientific Commissioners had to choose between different assessments and their consequences without detailed knowledge of why the differences arose (see SC-CAMLR, 1987, for a typical example of an assessment of mackerel icefish at South Georgia, where the estimates of yield varied by a factor 3). Within the Commission, the implementation of catch limits, as with any conservation measures, required consensus and often resulted in majority advice from the Scientific Committee for lower catch limits being ignored.

The inability of the Commission to take account of the uncertainties in management advice from the Scientific Committee led to considerable frustration on the part of scientists participating in CCAMLR. Frustration was also generated by the reliance on assessment methods that attempt to identify optimal rates of harvesting from fish stock production models. The Commission had adopted in 1988 a target fishing mortality of F0.1 for all fish stocks, but this level was likely to be too high to enable recovery of depleted species (de la Mare and Constable, 1991), as well as being likely to be inappropriate for mackerel icefish and for allowing maintenance of mesopelagic fish populations (SC-CAMLR, 1991).

The frustration resulted in a strong statement by scientists on the capabilities of the science to provide unequivocal advice on catch limits (SC-CAMLR, 1990, Appendix D, Annex 5); a statement that paralleled disquiet amongst scientists concerned with management of living resources elsewhere (Ludwig *et al.*, 1993). The statement on uncertainty was endorsed by the Commission in 1990. This did not result immediately in a method by which scientific consensus could be achieved, such that uncertainty could be unambiguously and unanimously dealt with in the management of Antarctic fisheries. However, it did signal a change towards a precautionary approach by the Commission.

Developing a precautionary approach, 1986–1996

Discussions on how to embrace the objectives set out in Article II arose during early meetings of the Scientific Committee (Australia, 1985a; Beddington and de la Mare, 1985; Butterworth, 1985). In 1985, the Commission was presented with a framework for evaluating management procedures based on simulations that tested whether management measures are highly likely to meet the objectives they are set to achieve (de la Mare, 1987). This formed the precursor of discussions in the Commission Working Group on the Development of Approaches to Conservation (1986–1990), but no consensus was achieved. Instead, the Commission continued to rely on reacting to problems as they arose (de la Mare, 1996).

Nevertheless, operational objectives were developed that took account of the general principles in Article II and provided the background necessary for developing assessment methods that were (i) better directed at achieving the general objectives of the convention, (ii) more able to take uncertainty into account, and (iii) more able to achieve consensus on specific catch limits through the application of agreed decision rules.

Two parallel actions facilitated the development of these operational objectives – the elaboration of important criteria for managing krill and a similar elaboration of target levels of recovery for depleted species. The latter case showed the Commission how computer simulation studies can be used to evaluate different management strategies, in this case for the restoration of stocks. It also provided an example of how uncertainty can be taken into account when developing these strategies (see for further discussion CCAMLR, 1990 Annex 7; de la Mare and Constable, 1991).

In the case of krill, two years of debate ended with the Commission (CCAMLR, 1991, paragraph 6.13) endorsing the advice of the Scientific Committee "that reactive management – the practice of taking management action when the need for it has become apparent – is not a viable long-term strategy for the krill fishery. Some form of feedback management, which involves the continuous adjustment of management measures in response to information, is to be preferred as a long-term strategy. In the interim, a precautionary approach is desirable and in particular, a precautionary limit on annual catches should be considered." This resulted in the first precautionary catch limit for krill being set in 1991 and the first explicit recognition of the need for precautionary measures prior to the development of feedback management procedures (Nicol and de la Mare, 1993).

Development of decision rules

By 1990, the Commission had endorsed the general concepts for setting catch limits for krill (SC-CAMLR, 1990, Annex 4):

- to keep krill biomass at a level higher than would be the case for single-species harvesting considerations and, in so doing, to ensure sufficient escapement of krill to meet the reasonable requirements of predators,
- given that krill dynamics have a stochastic component, to focus on the lowest biomass that might occur over a future period, rather than on the average biomass at the end of that period, as might be the case in a single-species context, and
- to ensure that any reduction of food to predators which may arise out of krill harvesting is not such that land-breeding predators with restricted foraging ranges are disproportionately affected compared with predators in pelagic habitats.

These concepts resulted in rules for deciding precautionary catch limits for krill, which were adopted in 1994 and aimed to determine a long-term annual yield that satisfied the decision rules. The application of the rules is derived from the basic approach of Beddington and Cooke (1983), and applied to krill by Butterworth *et al.* (1992), where yield is calculated as a proportion (γ) of an estimate of the pre-exploitation biomass (B_0). The three-part rule for krill is: (i) choose γ_1, so that the probability of the spawning biomass dropping below 20% of its pre-exploitation median level over a 20-year harvesting period is 10%; (ii) choose γ_2, so that the median krill escapement in the spawning biomass over a 20-year period is 75% of the pre-exploitation median level; and (iii) select the lower of γ_1 and γ_2 as the level for calculation of krill yield.

The calculation of a long-term annual yield does not imply that a catch limit of that amount will be retained for the total period. The estimate of yield would be revised as new information or improved methodologies arose. However, it does provide a basis for setting catch limits over a number of years rather than attempting to revise catch limits each year, a strategy which had failed for managing finfish stocks in CCAMLR.

The first two criteria of the decision rule relate to objectives 3(a) – the ‘‘recruitment criterion’’ – and 3(b) – the ‘‘predator criterion’’ – in Article II, respectively, while the length of time over which the risk is evaluated (20 years) relates to 3(c). Thus, these rules provide the first example of specifying the objectives of CCAMLR in scientifically interpretable and measurable terms.

The levels used in the two criteria are arbitrary and they will need to be revised from time to time. The recruitment criterion will need to be revised to take into account any information that becomes available on the relationship between stock and recruitment. Revising the predator criterion depends on better information on the functional relationship between abundance of prey and recruitment in predator populations. The 75% level has been chosen as the midpoint between taking no account of predators (i.e. treating krill as a single-species fishery and, thereby, choosing a level of escapement at 50%), and providing complete protection for predators (i.e. no krill fishery). CCAMLR has begun to develop models to explore the possible form of these functional relationships.

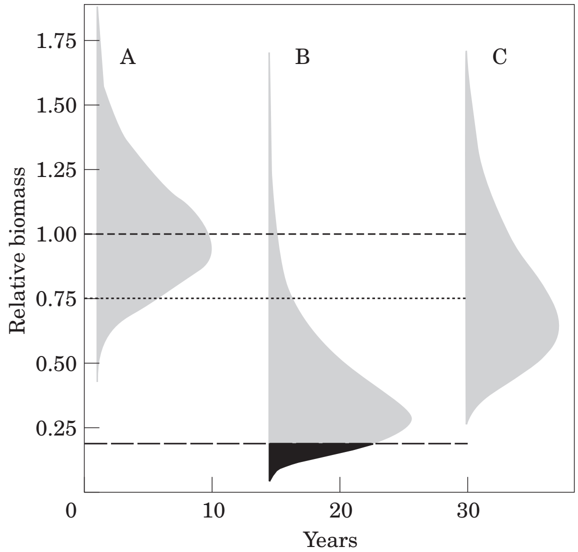

Figure 3. Statistical distributions of krill spawning biomass obtained by ‘‘Monte Carlo’’ projections of a population model that takes into account the effects of uncertainties in krill demography and unexploited biomass: Distribution A represents the potential unexploited biomasses (dash line: median); B is the statistical distribution of lowest population biomasses under a constant catch limit selected so that the probability of the biomass dropping below 20% of the pre-exploited median level over a 20-year harvesting period is 10% (large-dashed line); C is the statistical distribution of biomass at the end of 20 years of exploitation under a constant catch limit selected so that median escapement at the end is 75% (dotted line) of the pre-exploited median level. For further explanations see text.

Applying the rules in krill assessment

Precautionary catch limits for krill are calculated probabilistically using Monte Carlo integration. A simple population model, which includes random variability in recruitment, is run hundreds of times with values for growth, mortality, and abundance drawn at random from suitable statistical distributions, to allow natural variability in the population as well as uncertainty in the parameter estimates to be incorporated. Thus, the simulation model is used to calculate a distribution of possible population sizes both in the absence of fishing and at various fishing mortalities. These distributions are used to determine the proportion (γ) of an estimate of the unexploited biomass (B_0; from a hydroacoustic survey) that can be caught each year (de la Mare, 1996).

Each of the many simulations starts with a biomass of krill drawn from a statistical distribution that reflects the properties of the biomass survey estimates. The biomass is divided into a number of age classes. In each simulation year, the biomass is recalculated by adding an amount for annual growth and deducting an amount corresponding to natural mortality. The biomass of each year's recruits is added and the constant annual catch of γB_0 is deducted. Variability in the simulated population biomass in each year arises because the recruitment varies from one year to the next. Annual recruitment is drawn from a statistical distribution that reproduces the statistical properties of the estimates of proportional recruitment (obtained from the length compositions collected during krill surveys; de la Mare, 1994a, b).

The value for γ is selected, which gives a statistical distribution of the outcomes of all simulations that meet the criteria (Fig. 3). The model is run with $\gamma = 0$ (i.e. no catches) to produce the distribution of unexploited spawning-stock biomass (distribution A). This distribution determines the median unexploited spawning-stock biomass. When γ is greater than zero, the simulated biomass is reduced by the effects of fishing.

The first criterion requires the value of γ, which leads to a 10% probability of the spawning biomass dropping below 20% of its pre-exploitation median level over a 20-year harvesting period. Applying this criterion requires the examination of the statistical distribution of the lowest population size (in terms of spawning biomass) in any year over the 20 years of each simulation, collected over hundreds of replicates. The probability of attaining a lowest spawning biomass less than 20% of the pre-exploitation biomass is estimated from the relative frequency of this event over the set of replications. This is done for a range of values of γ. The required value γ_1 is that which has this relative frequency at 10% (distribution B).

The second part of the rule also leads to a value of γ, which is determined by the statistical distribution of spawning biomass at the end of the 20-year period in each simulation (Fig. 3). The selected value γ_2 is that which results in distribution C having a median that is 75% of the median of distribution A.

The values of γ_1 and γ_2 will usually be different, and so the third part of the decision rule chooses one of the two. Whether γ_1 or γ_2 is the greater depends largely on the degree of variability in recruitment and on the variance of the estimate of unexploited biomass B_0. The lower value is chosen because it means that the criterion corresponding to that part of the decision rule is just attained, and the criterion corresponding to the higher value will be exceeded. Choosing the higher γ would automatically lead to a failure to fulfil one or other of the two criteria. The obtained critical γ of 0.116 (SC-CAMLR, 1994) has subsequently been used to determine catch limits for krill.

Generalizing this approach

The same approach has been developed within CCAMLR into a Generalized Yield Model (GYM) (Constable and de la Mare, 1996). The application of the method is illustrated by the changes required to assess precautionary catch limits for Patagonian toothfish. Until 1994, the Working Group on Fish Stock Assessment had endeavoured to use conventional methods of stock assessment. However, these methods suffered from uncertainties in model parameters as well as from an inability to estimate the status of the stock. Data from the long-line fishery were insufficient and fishery-independent surveys could not access the adult portion of the stock. Thus, no estimate of B_0 was available. Also, the catch history needed to be accounted for in the assessment as the fishery had already begun.

These two problems were addressed by using absolute estimates of the abundance of recruits and projecting these forward in the simulations. This enabled the known catches to be directly discounted from the population. In so doing, the long-term annual yield could be assessed in tonnes rather than as a proportion of an estimate of B_0. Fortunately, many groundfish surveys around South Georgia are available to estimate recruitment of age 4 fish (following the method of de la Mare [1994a]) and these have been used to estimate the parameters of a lognormal recruitment function. Thus, estimates of long-term annual yield for a long-line fishery have been available for South Georgia since 1995 (SC-CAMLR, 1995). The same methodology has been applied to the trawl fishery around Heard Island where a similar, though shorter, time series of recruitment surveys is available (Williams and de la Mare, 1995).

For each species, consideration needs to be given to the structure of the first two criteria in the decision rule. For example, Patagonian toothfish, as a large predator, is unlikely to constitute much of the diet of seals and birds (SC-CAMLR, 1997). Therefore, the species is considered in a single-species context and the second criterion is applied at the 50% level rather than at the 75% level.

An unusual case is the mackerel icefish, which is a prey species and therefore should have the predator criterion applied as for krill. However, it fails to meet the recruitment criterion even without fishing because of its high recruitment variability (de la Mare *et al.*, 1998) and, for stocks around South Georgia, because of sporadic years with high natural mortality owing to predation by fur seals when krill abundance is low (Agnew *et al.*, 1998). Modifications to the decision rules have been proposed to overcome this problem (de la Mare *et al.*, 1998; Agnew *et al.*, 1998).

In addition to reviewing the structure of the decision rule for each species, the manner in which assessments are undertaken is contingent on the state of available knowledge and methodologies. Assessing long-term annual yields provides a means of incorporating many uncertainties in a single assessment, so represents a precautionary approach. In particular, precautionary catch limits take account of the periods in which the stock has naturally fallen to a low level. As they are based on a constant catch over a 20–30 years' period, there is no need for annual reassessments.

If strong year classes are present then the population may be able to support catches above the precautionary level for one or more years. Consequently, the use of long-term annual yields may result in foregoing increased catches when the stock is abundant. While no strategies for short-term adjustments to catch limits have been evaluated as yet, a procedure has been used in the interim to enable short-term assessments of yield of mackerel icefish (de la Mare *et al.*, 1998). This requires a recent survey of pre-recruits followed by an assessment of yield based on the predator criterion. The short-term assessments provide estimates of catches over 2 years ahead that result in 75% of the stock escaping the fishery at the end. Two years corresponds to the time a cohort remains in the fishery. This methodology remains to be evaluated, using simulations, in the larger context of satisfying the decision rules in the longer term.

Managing new fisheries

The development of any fishery should not occur at a rate faster than the Commission is able to evaluate its potential consequences and whether the objectives in Article II would be met (CCAMLR, 1989, 1990). To this end, the Commission adopted measures requiring members to notify their intention to undertake a new fishery in the Convention Area (Conservation Measure 31/X; CCAMLR, 1991) and their intention to undertake further exploration following the initiation of a fishery (Conservation Measure 65/XII; CCAMLR, 1993). These measures provide the opportunity to authorize fishing activities in the Convention Area, ensuring that these activities remain sustainable. This important requirement for fisheries management has been identified by FAO (1995) in relation to the precautionary approach.

These requirements enable the Scientific Committee to evaluate the types of limitations to fishing operations that may be required in the early stages to satisfy conservation objectives while enabling reasonable prospecting within the new fishery. In the exploratory phase, the Scientific Committee will specify the types of information to be submitted that will facilitate assessments of the fishery, including research activities that may be required.

Measures so far imposed on new fisheries have included conservative catch limits for different management areas combined with local catch limits to avoid over-exploitation of localized stocks. For example, these apply to the new fisheries for Patagonian toothfish that have been requested in recent years on most banks and island shelf areas in the Subantarctic. The difficulty with identifying appropriate catch limits to enable prospecting has been the absence of survey information of recruits in these locations. In the interim, the generalized yield model has been used by prorating the estimates of recruitment from fished areas to other areas based on the ratios of sea-bed area. Given the uncertainties surrounding the assumptions that stocks on the new grounds have the same characteristics as known stocks, the Commission discounted the yield estimates, such that catch limits were set at 0.4 times the estimate of yield provided for each statistical area. The Commission also prevented all catch from being taken in a small area by restricting the catches to 100 t per rectangle of 1° longitude by 0.5° latitude. The development of an overall management procedure with prospective evaluation of different methodologies remains to be undertaken. Some immediate priorities for research include recruitment surveys on the new fishing grounds and evaluation of demographic and growth parameters in these areas.

Experimental and survey regimes have been successfully initiated in exploratory fisheries for crabs around South Georgia Island as well as for Patagonian toothfish in some areas.

By-catch

Recently, a general approach has been adopted for managing by-catch species, notably that catch limits be set for each by-catch species in each statistical area and that measures be adopted to prevent localized effects or targeting by commercial operations (SC-CAMLR, 1998). The effect of these measures is that some fisheries may potentially be closed before the catch limit for the target species is reached. Sufficient information has been available to undertake assessments of precautionary long-term yield for some species, e.g. *Lepidonotothen squamifrons* and *Channichthys rhinoceratus* at Heard Island (Constable *et al.*, 1998). Other species for which no assessments are available, such as skates and rays, have had a catch limit of 50 t applied. To avoid localized effects, the Commission has adopted trigger levels of by-catch that signal when a vessel must move from a fishing ground if the rate of by-catch is too great (CCAMLR, 1998a).

Long-line fishing is considered responsible for the decline in the wandering albatross (*Diomedea exulans*) population at Bird Island, South Georgia and at Crozet Island (Croxall *et al.*, 1990; Weimerskirch and Jouventin, 1987). Conservation Measure 29/X (CCAMLR, 1991) has been set in place in an attempt to mitigate seabird mortality. Setting lines at night is effective, though only during the Antarctic winter. The most important measures are those which make the baited hooks unavailable to birds, either by shooting the lines underwater or by ensuring the lines sink sufficiently fast to depths below the diving depth of the albatross (Robertson, 2000). These methods are still under development.

Monitoring ecosystem effects

The indirect effects of fishing are most likely to arise from potential alterations to the trophic dynamics in the system (SC-CAMLR, 1995 Annex 4). The impacts of different harvest strategies can only be predicted by understanding the relationships between the fisheries, target species, and predators of the target species. Predictive models of these relationships are required for refining the decision rules underpinning the krill and generalized yield models or for developing new approaches for assessing catch limits. These models are also needed for designing monitoring programmes that can provide feedbacks on the effects of fishing and for signalling when changes to harvest strategies may be required.

Despite the apparent simplicity of the system, the effects of a krill fishery on krill predators may be difficult to detect because of spatial and temporal variability in the dynamics of the Antarctic marine ecosystem (Murphy *et al.*, 1988). Predators may switch to other prey when krill is unavailable (Agnew *et al.*, 1998), and the availability of krill in some areas, such as South Georgia, may be dependent on influx rather than resulting from local production (Murphy *et al.*, 1998). Thus, fishing upstream of predator foraging areas may be as important as the local fishing activities. Some important physical and biological interactions to be considered in a model of this system have been identified (SC-CAMLR, 1995 Annex 4). However, models of factors influencing the availability of krill to predators are in their infancy (Murphy *et al.*, 1998) and few models have examined the consequences of different levels of krill availability to predator populations (Butterworth and Thomson, 1995; Mangel and Switzer, 1998). Consequently, quantitative predictions of indirect effects of krill harvesting are difficult to formulate at present.

CCAMLR Ecosystem Monitoring Program

In 1986 members agreed that a mechanism was required to monitor the effects of fishing on the ecosystem. The Scientific Committee realized at the outset that monitoring the entire ecosystem would be highly impractical. Thus, the scope of the CCAMLR Ecosystem Monitoring Program (CEMP) was deliberately restricted to monitoring a few selected predators in a few areas. A full review is provided by Agnew (1997). We provide a brief summary.

A set of critical prey items was selected for their key positions in Antarctic ecosystems and their potential as harvestable resources: antarctic krill, Antarctic silverfish (*Pleuragramma antarcticum*), early life stages of fish, and *Euphausia crystallorophias*. The latter species replaces antarctic krill in some regions of the high-Antarctic. Selection of predators was based on the criteria that they feed predominantly on the prey species identified, have a wide geographical distribution, and represent important ecosystem components, that their biology was sufficiently understood and that sufficient baseline data exist to construct a scientific monitoring programme. The present list contains crabeater (*Lobodon carcinophagus*) and Antarctic fur seals (*Arctocephalus gazella*) and Adelie (*Pygoscelis adeliae*), chinstrap (*P. antarctica*), gentoo (*P. papua*), and macaroni (*Eudyptes chrysolophus*) penguins, Antarctic (*Fulmarus glacioides*) and cape (*Daption capense*) petrels and black browed albatross (*Diomedea melanophris*).

A core set of sites was chosen from within three defined Integrated Study Regions – around South Georgia Island and the Antarctic Peninsula in the Atlantic sector and Prydz Bay/Mawson Coast in the Indian sector (Fig. 2). A wider network of sites complements the research within these regions. Within each region, sites were chosen so that distinctions between broad-scale and local-scale changes, and changes occurring in fished areas versus non-fished areas, may be detectable. However, the choice was limited by practical considerations and the presence of established bases and long-term data sets. Selection of "control" sites proved problematic, because the geographical scale of the effects was expected to be large. Finding comparable sites outside such large areas that had similar environmental and biological characteristics, and where the collection of monitoring data was logistically feasible, was extremely difficult.

Several parameters are monitored for each predator species. The temporal and geographic scales over which these parameters are expected to integrate changes in the status of the ecosystem vary from several weeks and local (reflecting the duration of foraging trips: chick diets and growth) to annual/semi-annual, and region-wide (weight of birds arriving to breed breeding success, population size).

Sea-ice and hydrographic conditions are both important features governing the distribution, abundance, movements, and recruitment of krill as well as the distribution, winter survival, and timing and access to breeding colonies of its predators. Methods for monitoring environmental parameters of sea-ice cover, local weather, and snow cover have been agreed to date. Other parameters for monitoring the environment and prey species condition are currently being developed.

Fieldwork and data acquisition are carried out voluntarily by member states. Data collected are submitted to the CCAMLR Secretariat and used in annual ecosystem assessments (e.g. SC-CAMLR, 1998 Annex 4). Trends in the monitored parameters and anomalous years are identified for each species and site, and explanations for these phenomena are sought from examination of the monitored parameters of harvested species and the environment.

Using CEMP data in management

Although aspects of the ecosystem have been monitored since 1987, there is no indication of how these, or other types of data, could be used to demonstrate ecosystem effects of fishing and thereby initiate action by the Commission. An important question that needs to be addressed is "How much of the system needs to be monitored to effectively achieve the objectives of the Convention?"

For CEMP to be used in managing fisheries according to Article II, two more specific objectives need to be addressed. The first is to detect effects of fishing in sufficient time for decisions to be taken before irreversible damage is incurred. The second objective is to foresee whether changes in the environment may require re-assessment of the controls on fishing. For example, a continued long-term decline in sea-ice extent (de la Mare, 1997) may affect the demography and productivity of krill (Loeb *et al.*, 1997) and, consequently, a re-assessment of catch limits would be required. To meet both objectives, it is also important to be able to distinguish effects of fishing from the effects of natural variation in the environment.

An important requisite of the monitoring programme is for the data to be interpreted consistently, such that the same decision is likely to be made if the same information is presented irrespective of the time or circumstance. While this is a straightforward requirement, the accumulation of data on parameters representing the biological and physical components of the system, in combination with their variable interrelationships or degree of correlation, increases the probability of inconsistent and erroneous decisions. A major task is to determine how these data may be synthesized in a way that provides a quantitative basis for making decisions. A second task is to identify what variation in these parameters constitutes ecologically significant variation to which the Commission must respond in setting regulations.

The development of ecosystem assessments has proceeded for krill predators since 1997. Currently, this assessment comprises visual inspection of trends in the many predator parameters being monitored at the various sites around the Antarctic coupled with conceptual models considered appropriate to explain the trends. The working group has come to the conclusion that a more rigorous approach is required in order to meet the two main objectives of a monitoring programme.

In the first instance, the working group has concentrated on indicators of the status and breeding success of krill predators. To facilitate decision-making, a means to summarize the many measured parameters into a single index has been proposed by de la Mare and Constable (2000). Applying such indices in management will require determining how sensitive they are to assumptions about the functional relationships between species, between species and the physical environment, and between the fishery and krill. To be useful, an index must be sensitive only to those factors in which managers are interested and robust against others.

A major task remains to determine the magnitude of changes in the indices, or in individual parameters, which would signal that action needs to be taken by the Commission. There is as yet no solution as to what is required, although it is recognized that extreme values in a naturally varying system may be as important as detecting anomalous values.

The manner in which the effects that fishing has on the status of a species (or one or more of its demographic parameters) can be distinguished from natural variation or long-term trends in the environment has been discussed periodically since the early years of CCAMLR. In 1984, a proposal was put forward for establishing a series of fishing areas and closed areas as a large-scale experiment to help distinguish between these two types of effects (Australia, 1985b). A similar proposal was put forward again in 1992 with an elaboration of a feedback management procedure for krill (Constable, 1993). So far, there has been no commitment to an experimental approach to solving this question. Much of the debate has been centred on the role of long-term baseline data sets (e.g. Croxall, 1989). Strategic modelling is required to determine the appropriate form of a monitoring programme, including the number of parameters and types and scales of a design. The paucity of functional models of the Antarctic ecosystem is not sufficient

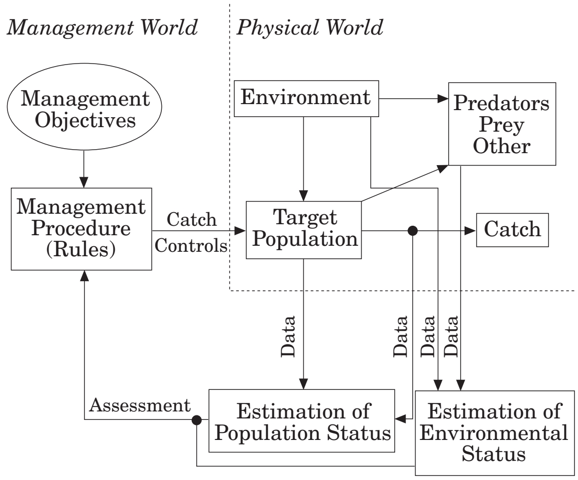

Figure 4. Schematic overview of a living resource management system as it would apply in the ecosystem context of CCAMLR (after de la Mare, 1996). A management procedure may be regarded as a set of rules which designate catch limits or other management measures as both a function of a set of management objectives and assessments of the state of the exploited populations. This definition emphasizes that catch controls change if management objectives are changed. The state of the target population depends on both the effects of exploitation and variations arising from changes in the physical environment and/or in the functional relationships with other species.

reason for deferring the evaluation of methods for detecting the effects of fishing. Such evaluation may help identify priority areas for research and information that would lead to better model construction and reduced uncertainty in quantifying the incidental effects of fishing.

Future directions

While CCAMLR now uses a precautionary approach to setting catch limits for its fisheries, it remains to be determined whether the current methods used to assess catch controls on single species, to predict the effects of fishing, and to monitor the ecosystem, are sufficient to avoid changes that are irreversible over 20–30 years. Management should be based on an explicit paradigm consisting of the following elements: (1) objectives that are measurable; (2) a procedure based on decision rules; (3) assessments based on specified data and methods; and (4) a prospective evaluation of the management procedure using performance measures (de la Mare, 1998).

A simplified form of this process as adapted for CCAMLR (Fig. 4) shows the essential linkages between different kinds of data acquired from monitoring the target species and the ecosystem and how they need to contribute through assessments to the management procedure. Actions to adjust fishing activities are taken when the assessed status of the stocks, or of the system, are at critical points identified in the decision rules. The most important element is to evaluate possible management procedures to see if they can work in principle, using simulation or other methods (de la Mare, 1996, 1998). To carry out such evaluations, the objectives for management need to be specified in a scientifically interpretable way and the kinds of observations that can be reliably obtained about the exploited population and the ecosystem need to be considered. We need also to develop models for both the resource and the patterns of operation of the fisheries.

The utility of various types of information needs to be evaluated in the context in which it will be used. This is particularly important as CCAMLR relies on voluntary research by member countries. Thus, it is important to identify the most cost-effective research programme to provide the most important data for management. Although a method may seem to give disappointing accuracy or precision, this does not necessarily mean that it will fail to work in practice. Conversely, a method that gives precise estimates of some parameter may not be sufficient for achieving the management objectives. This can only be found out by some form of analysis or test, and the best time to carry out testing is before trying it out in the real world. De la Mare (1996) showed the feasibility of this approach and how evaluating possible management procedures does not require scientists to agree that any given effect may or may not happen, only that it cannot be ruled out. This is clearly a more tractable consensus than getting scientists to agree that an observed change in a fish stock is due to overfishing, and that a given management action will rectify the problem.

By developing management procedures based on decision rules, decisions about management are made prospectively: agreements about what to do when certain situations arise are made in advance. If the management procedure has been shown to be sound, there may even be a reasonable chance that pre-agreed decision rules will be followed. The CCAMLR experience has demonstrated that obtaining consensus to make difficult adjustments only after the need for them has become apparent presents a major problem.

Concluding remarks

CCAMLR has responsibility for managing large-scale fisheries. The toothfish fishery extends throughout the Antarctic. The krill fishery can become the largest global fishery (Nicol and Endo, 1997) and consequently has the potential to significantly affect the trophic structure of the Antarctic ecosystem. These fisheries also have an international context where agreement between 23 members is required for management measures to be set in place and, ultimately, the co-operation of non-members is also necessary for ecological sustainability to be achieved in the longer term.

This context provides an ideal forum for the development of international methodologies to achieve ecological sustainability in fisheries. CCAMLR has already grappled with many of the ecological issues now facing fisheries around the world and has agreed a number of principles and approaches for achieving conservation objectives. To this end, it has been an innovative and prescient convention. However, the failure of Antarctic fisheries cannot now be attributed to the inherited fisheries that had already failed historically. While the precautionary approach is now entrenched in its work, essential work is still required to develop management procedures that are robust against the unknown and uncertain behaviours of the Antarctic ecosystem. The CCAMLR experience provides two important lessons. First, conservation objectives can only be achieved by implementing management measures even when very little is known. Secondly, methods have been found for achieving scientific consensus despite the uncertainties surrounding estimates of parameters and the behaviour of the system. This is an essential element in the management of international fisheries and is increasingly important in the management of many coastal-state fisheries as well.

CCAMLR is yet to face the real test in its ecosystem approach. The krill catch is currently low compared with the long-term precautionary yield. Future expansion of the fishery appears inevitable. Before this occurs, appropriate management procedures must have been developed to avoid localized effects on the ecosystem and to provide effective feedbacks on the effects of fishing.

Unfortunately, CCAMLR suffers from the inherent weakness of international conventions where achievement of objectives is based on the co-operation of many members and on recognition of measures by non-members. The pressures of illegal, unreported, and unregulated fisheries have shown the necessity for the wider international context of fisheries to be recognized. The toothfish fishery is currently unsustainable because it is driven by forces beyond the scientific approaches to management developed. There is an urgent need for global action on over-capacity in fisheries and a requirement of global controls on fishing operations to ensure ecological sustainability can be achieved locally.

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